Quality Management by Warranty Contract Under Dual Asymmetric Information

Chen, Zhihua; Lan, Yanfei; Li, Xiang; Shang, Changjing; Shen, Qiang

Published in:
IEEE Transactions on Engineering Management

DOI:
10.1109/TEM.2020.2972563

Publication date:
2022

Citation for published version (APA):
Chen, Z., Lan, Y., Li, X., Shang, C., & Shen, Q. (2022). Quality Management by Warranty Contract Under Dual Asymmetric Information. *IEEE Transactions on Engineering Management*, *69*(4), 1022-1036. https://doi.org/10.1109/TEM.2020.2972563

Quality Management by Warranty Contract under Dual Asymmetric Information

Zhihua Chen, Yanfei Lan, Xiang Li, Changjing Shang, and Qiang Shen

***Abstract*—Product failure resulting from sourcing supplier's defective component has compelled a brand owner to enhance quality management, especially when the supplier has informational advantage. We examine a brand owner's problem of screening a certain supplier's inherent quality level with an attempt to induce supply chain partners' quality efforts using the warranty contract based on information acquired from inspection technology. A supplier's inherent quality level is herein determined by the private information held by the supplier and is typically characterised as an uncertain variable. The optimal warranty contracts and the expected profits of the brand owner and the supplier are derived from four different scenarios under the framework of uncertainty theory and principal-agent theory. We find that under the condition of pure double moral hazard or pure adverse selection, the first-best outcomes can be achieved without incurring agency cost under the designed contract. However, double moral hazard combined with adverse selection often leads to under-investment in quality efforts as the supplier can shirk by misreporting her type. Consequently, we present the menu of warranty contracts to screen the supplier's private information. Finally, we provide empirical managerial recommendations on mitigating potential adverse impacts caused by information asymmetry, supported with numerical investigations.**

***Index Terms*—Quality management, Uncertainty theory, Adverse selection, Double moral hazard, Warranty contract.**

I. Introduction

Quality management has arguably become a more challenging task for many brand owners because nowadays, product components are usually outsourced from independent suppliers, rather than from the subdivisions of an integrated supply chain. In a supply chain involving collaboration, improving end-product quality will normally extend beyond the boundaries of the firms' in-house process capabilities. If the components delivered by a supplier break down or faults occur within the brand owner's manufacturing process, there will be product defects and the defective product will often result in a large number of product recalls and a huge profit loss: the repair/replacement cost and opportunity costs such as lost sales due to customer dissatisfaction for the brand owner. For example, in 2017, Boeing suspended 737 MAX flights after being informed of a potential quality issue about the aircraft's LEAP-1B engine provided by an independent supplier CFM International Company. As a result, aircraft delivery would be delayed, thereby affecting the Boeing's customer dissatisfaction and company reputation.[1] In the electronics industry, in April 2016, due to the explosion of the battery outsourced and bought from the supplier ATL, Samsung announced a recall of 3.6 million Galaxy Note 7 and suffered a loss of \$5 billion cost.[2] There are also many examples to display that product defects will affect a brand owner's current and future profits. This means that any brand owner has to take quality management seriously, necessitating a deeper understanding of the quality improvement incentives to ensure better product performance.

In supply chain quality management, the supplier may have private information about its inherent quality level causing adverse selection, whilst the supply chain partners' quality efforts are generally not observable and contractible to each other causing double moral hazard [1]. Even through the brand owner takes on serious quality check or conducts quality audits at its potential suppliers' facilities, only the incoming average quality may be known which is achieved jointly by both the inherent quality level and the quality efforts. The brand owner may not be able to distinguish the supplier's accurate inherent quality level and quality effort level, which is detrimental to the brand owner for enhancing product quality and revenue. For example, in 2007, since Samsung could not screen ATL's quality details (e.g., inherent quality level and quality effort) while trying to ensure improved performance of battery quality, Samsung decided to terminate its collaboration with the supplier ATL.[3]

As indicated above, dual asymmetric information (e.g., hidden information and hidden actions) result in adverse selection and double moral hazard problems and makes it difficult to achieve good product quality, which may significantly compromise the potential profit for the brand owner. Specially, "double moral hazard" is subordinate to "dual asymmetric information" and they have different meanings. We mainly study the contracting relationship between the brand owner and

This work was partly supported by the National Natural Science Foundation of China [grant numbers 71771166, 71722007 and 71771165], partly by the Fundamental Research Funds for the Central Universities (buctrc201926) and partly by a Sêr Cymru II COFUND Fellowship, UK. (*Corresponding author: Yanfei Lan*.)

Z. Chen is with the College of Management and Economics, Tianjin University, 300072, China, (e-mail: zhihuachen@tju.edu.cn.

Y. Lan is with the College of Management and Economics, Tianjin University, 300072, China and Department of Computer Science, Aberystwyth University, Aberystwyth SY23 3DB, UK, (e-mail: lanyf@tju.edu.cn).

X. Li is with the School of Economics and Management, Beijing University of Chemical Technology, Beijing 100029, China and Department of Computer Science, Aberystwyth University, Aberystwyth SY23 3DB, UK (email: lixiang@mail.buct.edu.cn).

C. Shang and Q. Shen are with the Department of Computer Science, Aberystwyth University, Aberystwyth SY23 3DB, UK (email: cns@aber.ac.uk; qqs@aber.ac.uk).

[1] http://finance.sina.com.cn/chanjing/gsnews/2017-05-11/doc-ifyfekhi7280825.shtml

[2] http://www.donews.com/net/201609/2938501.shtml

[3] http://tech.ifeng.com/a/20170821/44666215_0.shtml

component supplier in the background of "dual asymmetric information", which includes adverse selection (i.e., the brand owner has to screen the supplier's private information about the accurate inherent quality level) and double moral hazard (i.e., neither the brand owner nor the supplier can observe each other's quality effort).

Furthermore, because the supplier's accurate inherent quality level is his private information, there is usually no observed historical data about the supplier's accurate inherent quality level, especially when the brand owner contracts with a new supplier [2]. This fact leads to that the probability distribution cannot be estimated from the frequency due to the lack of them. Hence, probability theory is no longer applicable to be used to characterize these incomplete information. Whereas uncertainty theory founded by [3] has been proved to be appropriate to model incomplete information without observed data by inviting some domain experts to evaluate the belief degree that each event will occur (e.g., [4], [5] and [6]). In this situation, the novel contribution is that using the uncertainty theory to characterize the incomplete information in supply chain quality management.

The revelation principle as per the principal-agent theory can provide support for the brand owner to screen the asymmetric information if a certain rational incentive mechanism can be devised [7]. Furthermore, the approach that combines warranty contract and inspection over incoming components has been widely adopt to ensure quality improvement (e.g. [8], [9] and [10]). Following this approach, the brand owner inspects an incoming component after receiving it from the supplier and penalises the supplier with warranty, based on the number of defective components identified during the inspection process.

We intend to provide a new perspective on how asymmetric information about the supplier's inherent quality level and unobservable effort may affect the brand owner's contract design and also, on supply chain partners' quality investment and optimal profits. In particular, the research questions addressed herein are as follows: How can a brand owner design the warranty contract under different information structures and how does information asymmetry influence the optimal contracting strategies? If exact information regarding the supplier's inherent quality level is not available or the quality efforts are not observable, can the brand owner design contracts to screen supplier type as well as to induce the first-best quality improvement efforts? How does information asymmetry impact upon the brand owner's and the supplier's optimal profits? Under what conditions is knowing the supplier's initial quality and contracting on supply chain partners' quality efforts valuable to the brand owner?

To answer these questions, we consider a two-tier supply chain in which a brand owner manufactures products using components directly bought from a component supplier. The supplier is privately informed about its inherent quality level and may make unobservable quality effort to improve the components' quality. When the brand owner receives the components delivered by the supplier, she will conduct inspection-based approach, i.e., the components will be inspected and the supplier will be penalised for all defective components identified by the inspection. Afterwards, the brand owner makes its own quality effort which cannot be observed by the supplier during the manufacturing process. Eventually, the brand owner sells to the consumer the final product whose quality is decided by the component and the manufacturing process. Thus, adverse selection (i.e., the brand owner has to screen the supplier's private information about the accurate inherent quality level) and double moral hazard (i.e., neither the brand owner nor the supplier can observe each other's quality effort) are presented. Also, this may incur an external failure cost if the product fails in the market. Supported with the framework of uncertainty theory and principal-agent theory, we examine the optimal warranty contract and supply chain partners' profits in different information scenarios.

The main contributions of this paper are listed as follows.

- We examine how the supplier's inherent quality level and unobservable effort affect the brand owner's contract design and also, on supply chain partners's quality investment and optimal profits under four information cases: complete information, pure adverse selection, pure double moral hazard, and combination of both double moral hazard and adverse selection.
- We derive the optimal warranty contracts and calculate both supply chain parties' profits under four information cases. Particularly, we demonstrate that in pure adverse selection case, the brand owner's first-best outcome can be achieved. However, the situation of both adverse selection and double moral hazard may lead to under-investment in quality efforts.
- We investigate the impacts of supplier's dual asymmetric information on the brand owner by comparing the brand owner's and the supplier's optimal profit, again with respect to the four information cases. Counterintuitive it may sound, we show that the brand owner's first-best outcome can be attained and the supplier's agency cost does not exist in both pure double moral hazard and pure adverse selection case by using the designed warranty contract.
- Relative to first-best, however, the combination cases with both double moral hazard and adverse selection result in a lower profit and a positive agency cost for the brand owner. Also, we identify three factors that determine the value of information for the supply chain partners, in terms of the profit differences between the case of complete information and that of combination of double moral hazard and adverse selection.

The rest of this paper is organised as follows. Section II reviews related literature. Section III presents the basic modeling framework. Section IV studies the optimal solutions under symmetric information about inherent quality level. Section V derives the optimal solutions under asymmetric information regarding inherent quality level. Section VI provides comparative statics. Section VII concludes the paper. All the proofs are provided in the "Appendix".

II. Literature Review

The work presented here intersects with the following research areas: the quality management in supply chains and the principal-agent approaches based on uncertainty theory.

The quality management literature mainly focuses on designing optimal quality improvement approaches in supply chains. [1] considered two contractual agreements of cost sharing based on selective root cause analysis and partial cost sharing based on complete root cause analysis, and showed that both contracts can achieve the first best effort levels. [2] analysed the impact of certification standards on the supplier's investment in quality by screening the supplier's investment in quality. [8] investigated a deferred payment mechanism, an inspection mechanism, and a combined mechanism of these for dealing with product adulteration problems in the single moral-hazard case and identified the conditions where the deferred payment mechanism may dominant the inspection mechanism. [11] modeled manufacturer's choice of inspection strategy and characterised the Nash equilibrium between a supplier and a manufacturer by embedding two compensation schemes of price rebate and warranty in the cost sharing contracts. [12] investigated the link between product design, supplier's investment and supply-chain efficiency, based on information from incoming inspection and external failure in the separable and non-separable product cases under double moral hazard. [13] examined the optimal warranty/penalty contract in the single and double moral hazard cases between a buyer and a supplier, based on incoming inspection and external failures. [14] studied the buyer's problem of inducing the supplier's quality effort using two arrangements: the appraisal regime and the certification regime, and gave the trade-off between these two arrangements. [15] looked into a supply chain contract problem by combining pricing with warranty when the supplier's product quality was unobservable and had a vagueness boundary to the buyer. [16] addressed the potential coordinating power of the revenue sharing contract in a supply chain for improving the design quality of a product in a two-stage game approach. [17] evaluated the relationship between hard and soft quality management and organisational context. [18] experimentally investigated how the monetary and relational incentives may affect the overall quality and supply chain efficiency in a two-tier supply chain. [19] tested how the buyer may manage the sourced quality by three instruments: investment, incentives, and inspection. [20] investigated the effects of mass customization and product modularity on supply chain quality integration and the impact of supply chain quality integration on competitive performance. [21] estimated the effect of supply chain proximity on product quality and found that defect rates were higher when upstream and downstream factories were farther apart. [22] proposed a new model integrating supply chain and IoT, referred to as SCoT, to evolve into SSCE and thus enhance supply chain productivity. Just as [9] stated, under inspection-based approach which manages quality completely based on inspection information on both incoming components, all quality-related activities in the supply chain were managed and contracted completely based on the outcomes of inspections. [23] studied the efficiency of inspection-based on out of control detection in wafer fabrication. [24] examined optimal inspection-based preventive maintenance policy for three-state mechanical components under competing failure modes. [25] developed an inventory model with lot inspection-based policy and found that optimal order size and sample size were intrinsically linked and maximize the total profit.

Different from the aforementioned previous studies, we contribute to this line of research by modelling the quality improvement incentives under uncertainty theory rather than probability theory, as none of supply chain members' effort choices is observable while there is information asymmetry with regards to the supplier's inherent quality level. That is, we mainly focus on dealing with the optimal warranty contracts in inspection-based approach (i.e., the brand owner inspects an incoming component after receiving it from the supplier and penalises the supplier with warranty, based on the number of defective components identified during the inspection process), by incorporating double moral hazard and adverse selection under uncertainty theory.

Uncertainty theory as coined in [3] has been widely utilised in characterizing human uncertainty (e.g., [26], [27], [28] and [29]). In particular, uncertainty theory has successfully used to model the principal-agent problems under uncertain environment. [30] established an uncertain contract model to cope with the employment relationship problem between an enterprise and rural migrant workers in the labor market. [31] discussed an uncertain principal-agent problem by characterising the incomplete information with uncertain variables and presented the so-called principal's decision rule based on confidence levels. [32] presented four uncertain principal agent models to investigate the impact of risk attitude upon incentives and performances in new product development. [33] put forward two classes of bilevel uncertain principal-agent monitoring models, namely, ideal information-based monitoring and effort-based monitoring. [34] investigated the impacts of private risk aversion magnitude and moral hazard when the risk aversion degree and the project variability are characterised as uncertain variables. [35] considered the external demand and the product substitution rate as uncertain variables and explored how cooperation decisions would affect preferred pricing timing. [36] analyzed a typical water-rail-road (WRR) intermodal transportation that was composed of three serial transportation stages: water, rail and road, and formulated an uncertain bi-level programming model for the incentive contract design problem under expectation and entropy decision criteria. [37] investigated a three-echelon supply chain problem in which quantity of defective components and demands of customers were all characterized as uncertain variables and three models under different criteria such as expected value criterion, chance-constrained one and measure-chance one were constructed. [38] investigated the impacts of the existence of cost salience and information asymmetry on the incentive contract and the project manager's profit within the framework of uncertainty theory and principal-agent theory.

Different from the above outlined previous studies in the principal-agent literature using uncertainty theory, our study originally contributes to applying the uncertainty theory to the area of quality management in supply chains while characterising the supplier's initial quality level as an uncertain variable. In so doing, this work helps investigate into the impact on quality improvement incentives in the scenarios involving asymmetric information.

III. Model Description

Consider a supply chain comprising a risk neutral brand owner and a risk neutral component supplier. The brand owner (e.g., Samsung) manufactures a product (e.g., Galaxy Note 7) using a component directly sourced from the supplier (e.g., ATL). Without losing generality, suppose that the brand owner plans to produce m units of the product and each finished product needs n units of the component. Thus, it procures a total of mn components from the supplier. For this investigation, as with the relevant literature [9], we set $m = 1$ and $n = 1$. The brand owner sells the final product to the final consumer and receives revenue r per unit with good quality, but incurs a failure cost of l per unit with bad quality, where l denotes the replacement/refund cost and the customer dissatisfaction cost.[4]

The supplier first makes a quality improvement effort for the component in its production process. The component's quality is determined by two factors: the supplier's inherent quality level x and its quality improvement effort e_S. Suppose that the component's quality is given by

$$q = e_S + x,$$

where $q \in (0, 1)$. Also, assume that the quality effort e_S is privately observed by the supplier with corresponding quality cost $S = \frac{1}{2}e_S^2$.[5] Furthermore, if the brand owner conducts incoming sampling inspections, the incoming average quality is then known to it but not the supplier's accurate inherent quality level. There is usually no observed historical data for the brand owner about the supplier's accurate inherent quality level, especially when it contracts with a new supplier (e.g., [1] and [2]). As a result, the brand owner can only make a subjective assessment about the supplier's quality level.

The above situation leads to the conclusion that the probability distribution cannot be objectively estimated from the limited information provided. As such, probability theory is very difficult, if not impossible to be applied to characterise the present problem. However, uncertainty theory [3] can help solve this problem, say, by inviting domain experts to evaluate the belief degree that each event may occur. Thus, we characterise the supplier's inherent quality level as an uncertain variable X with distribution $F(x)$ and density function $f(x)$ on the interval $[\underline{x}, \overline{x}]$, where $0 \leqslant \underline{x} < \overline{x} < 1$. We also presume the inverse hazard rate (IHR) $H(x) = (1 - F(x))/f(x)$ on initial quality level, with $H(x)$ decreasing in x. This monotonicity condition is commonly imposed in the private information agency literature (e.g., [30], [39] and [40]). Most parametric single-peak distributions have a decreasing IHR, such as linear, zigzag, normal and lognormal uncertain distributions (see [3] for details). Note that the similar assumption that the supplier's inherent quality and its quality effort are substitutes to each other is also adopted by other quality management literature (e.g., [1] and [15]).

Subsequent to the supplier's investment in the component, the brand owner may exert costly effort for improving the quality of the finished product in the manufacturing process. The brand owner's quality effort, $e_B \in (0, 1)$, performed for the desired functions in the manufacturing process has the corresponding cost $M = \frac{1}{2}e_B^2$. As with the literature, we assume that the supplier's quality in producing the component and the brand owner's quality in the manufacturing process are considered to be independent, that is, only both the manufacturing process and the component must be in good quality, can the finished product have a good quality (e.g., [9], [41] and [42]). From this, the ratio that a finished product is in good quality is given by qe_B.

A. *Incoming inspection-based approach*

To ensure the quality of the finished product and to reduce failure rate, the brand owner can implement a quality management program to screen the component supplied by the supplier. We consider the inspection-based approach in quality management, where the brand owner adopts inspection strategy to test the incoming components in a batch with a fixed cost of I (e.g., [8], [9] and [11]). The inspection mechanism is not perfect in detecting quality problems: it does not reject a good unit, nor does it identify all defective units. Denote the ratio of the inspection method identifying a defective component to be θ. This is equivalent to stating that the component rejection rate is $(1 - x - e_S)\theta$, where $(x + e_S) \leqslant 1$, ensuring that the component quality level is definite and limited. Thus, the total amount of defective finished product or the ratio of external failure $g(x, e_S, e_B, \theta) = 1-(e_S+x)e_B-(1-x-e_S)\theta$. If a defective product in the batch is found in the test, it will be returned to the supplier and all quality-related activities involved in component quality in the supply chain are managed and contracted, completely based on the outcomes of such inspections. Note that e_B and θ are independent. This is because as with the literature, since the quality of the manufacturing process and the quality of the component are independent, and the brand owner's quality effort exerting in the manufacturing process is a decision variable, while the ratio of the inspection method identifying a defective component θ is an exogenous variable which is determined in advance, so we assume these two are independent. We also show that the brand owner's optimal quality effort is decreasing in the ratio of the inspection method identifying a defective component in Propositions 1–4.

B. *Quality incentive by warranty contract*

In this work, the supplier's inherent quality level is deemed to be its private information and its quality effort is unobservable by the brand owner. That is, neither the supplier's inherent quality level nor quality effort is contractible to the brand owner. Therefore, from the brand owner's viewpoint, the optimal penalty/incentive mechanism should be designed in order to induce the supplier to choose the optimum quality effort and reveal its truthful inherent quality level. Here, we

[4] For example, Menu Foods, Ltd. suffered huge losses because of defective products imported from China. In this case, l includes the tangible losses such as revenue, stock price, class action lawsuits and intangible losses such as loss of goodwill and reputation (see http://www.sgma.com/press/).

[5] The quadratic function for cost has been used by [2] and [12]. In addition, as stated in [12] the specification allows us to derive near–closed form solutions for the endogenous variables and enables us to compare them in meaningful ways.

assume that the brand owner will contract the supplier with a two-part warranty contract (P,W), where $P(P \geqslant 0)$ is the up-front payment from the brand owner to the supplier and $W(W \geqslant 0)$ is the warranty payment paid by the supplier to the brand owner, contingent on the inspection information of the delivered components. Thus, the total payment that the supplier receives is given by

$$T = P - (1 - x - e_S)\theta W.$$

Overall, the sequence of events under inspection-based approach with warranty contract is described as follows:
(1) The brand owner first announces a menu of warranty contracts to the supplier.
(2) The supplier observes its own inherent quality level and then either accepts a contract from the menu or rejects the menu.
(3) If the brand owner and the supplier agree on the compensation (P, W), the brand owner pays the supplier an up-front payment P. The supplier then chooses quality enhancement effort e_S and supplies the component of the whole batch to the brand owner.
(4) The brand owner inspects the incoming component. If the component is identified as defective, the supplier pays W to the brand owner and the component is rejected. Otherwise, the brand owner accepts the component for manufacturing.
(5) The brand owner then makes the quality effort e_B in its manufacturing process. Afterwards, the finished product will be on sale in the market. If the finished product is sold with good quality, the brand owner will earn r. Otherwise, it will suffer from an external failure with a cost of l.

C. The supplier's and the brand owner's profit functions

The brand owner's expected profit is the product's revenue net of any external failure loss, any payment to/already made by the supplier and any inspection cost, which can be written as

$$\begin{aligned} \pi_B = \quad & E[r(X+e_S)e_B - l[1-(e_S+X)e_B - (1-X-e_S)\theta] \\ & -[P-(1-X-e_S)\theta W] - \tfrac{1}{2}e_B^2 - I]. \end{aligned}$$

As the brand owner does not know the supplier's inherent quality level exactly, a menu of contracts is offered by it for the supplier to self-select. However, for reducing the warranty payment to the brand owner while shirking the quality effort, the supplier may misreport its initial quality level as $\tilde{x}$. Given that the supplier reports the inherent quality level $\tilde{x}$ by self-selecting the contract $(P(\tilde{x}), W(\tilde{x}))$, whilst the truthful inherent quality level is actually x, the supplier's expected profit becomes

$$\pi_S(x, \tilde{x}) = P(\tilde{x}) - (1 - x - e_S)\theta W(\tilde{x}) - \frac{1}{2}e_S^2.$$

The first term in the supplier's profit function is the up-front payment the supplier would receive from the brand owner. The second term is the warranty the supplier pays the brand owner based on the component inspection outcome, and the last term is the cost of quality effort.

Correspondingly, if the supplier reports its inherent quality level truthfully by self-selecting the contract $(P(x), W(x))$, its expected profit is given by

$$\pi_S(x, x) = E\left[P(x) - (1 - x - e_S)\theta W(x) - \frac{1}{2}e_S^2\right].$$

D. Incentive problem

Since neither the brand owner's quality effort in the manufacturing process nor the supplier's quality effort in producing the component is observable and contactable, both the brand owner and the supplier choose their respective unobservable quality efforts as self-interest maximisers. In order to incentivise the brand owner's effort in manufacturing high-quality product, its incentive compatibility constraint for moral hazard can be represented as

$$\hat{e}_B = \arg\max_{e_B \geqslant 0} \pi_B.$$

Similarly, the brand owner should also design an incentive mechanism to make the supplier exert optimal effort in producing high-quality component. The supplier's incentive compatibility constraint for moral hazard can therefore be expressed as

$$\hat{e}_S = \arg\max_{e_S \geqslant 0} \pi_S(x, x), \quad \forall x \in [\underline{x}, \overline{x}].$$

As the supplier's inherent quality level is its private information, the incentive compatibility constraint for adverse selection should be introduced, which is given by

$$\pi_S(x, x) \geqslant \pi_S(x, \tilde{x}), \quad \forall x, \tilde{x} \in [\underline{x}, \overline{x}],$$

where $\underline{x}$ and $\overline{x}$ denote the possible minimum and maximum value of x, respectively. This is in order to ensure the supplier to report its inherent quality level x truthfully rather than claim another level $\tilde{x}$.

In addition, to ensure the supplier's participation in the warranty contract, its expected component utility should exceed the reservation utility obtained from any other options. Without loss of generality, we assume that the supplier's reservation utility is zero (which is also generally made in the principal-agent literature for representational simplicity (e.g., [43] and [44])). Thus, the supplier's individual rationality constraint is given by

$$\pi_S(x, x) \geqslant 0, \quad \forall x \in [\underline{x}, \overline{x}].$$

In the following, we will analyse the optimal quality incentive contracts under four different information acinarios so as to determine how the adverse selection and double moral hazard may affect the optimal warranty contracts, the brand owner's profits and the product's quality. The four information cases are summarised in Table 1, where the subsection numbers in the brackets stand for where each of these cases is to be addressed.

TABLE I
DIFFERENT INFORMATION CASES FOR INSPECTION-BASED APPROACH

Quality level	No moral hazard	Double moral hazard
Symmetric information	Case SO (§ 4.1)	Case SU (§ 4.2)
Asymmetric information	Case AO (§ 5.1)	Case AU (§ 5.2)

Throughout this paper, we denote e_S^{Z} and e_B^{Z} to be the supplier's optimal quality effort and the brand owner's optimal quality effort in case Z, respectively, where $\mathrm{Z} \in \{\mathrm{SO}, \mathrm{SU}, \mathrm{AO}, \mathrm{AU}\}$. Also, we denote the supplier's up-front payment and the warranty payment and the brand owner's optimal expected profit as P^{Z}, W^{Z} and π_B^{Z} in case Z, respectively. We now proceed to analyse each case when the warranty payment is based on information from incoming inspection.

IV. Symmetric Information about Inherent Quality Level

In this section, we focus on the optimal solutions under symmetric information regarding inherent quality level. In particular, we assume that the brand owner is fully informed about the supplier's inherent quality level (i.e., x is known with certainty). This usually occurs when the brand owner and the supplier have been working together for several years, and therefore the brand owner has a good idea of the supplier's truthful level of inherent quality.

A. Observable quality efforts

As a benchmark, we shall first determine the first-best solution of the model, in which the supplier's inherent quality is known and the brand owner and the supplier are fully informed about each other's quality improvement efforts. The brand owner's first-best profit and both parties' quality improvement efforts in this case will help further investigation into how such issues would be reflected in other cases. It will also aid in the understanding of whether the brand owner can design the optimal contract that achieves the first best profit from its supply chain partners.

Since there is no need for providing effort incentives and acquiring asymmetric information, the brand owner's optimisation problem in Case SO is to maximise the expected profit function π_B with respect to P, W, e_S and e_B, subject to the supplier's individual rationality constraint, which is given by

$$\begin{cases} \max\limits_{\{P,W,e_S,e_B\}} \pi_B \qquad (\text{OBJ–SO}) \\ \text{subject to:} \\ \quad \pi_S(x,x) \geqslant 0. \quad (\text{IRS}) \end{cases}$$

The first-best solution of the optimal warranty contract and the optimal quality investment efforts can then be obtained as follows.

Proposition 1: In Case SO, the optimal warranty contract is given by $P^{\mathrm{SO}} = \frac{1}{2}\left[\frac{x(r+l)^2-l\theta}{1-(r+l)^2}\right]^2$ and $W^{\mathrm{SO}} = 0$. The quality efforts of brand owner and the supplier are $e_B^{\mathrm{SO}} = \frac{(x-l\theta)(r+l)}{1-(r+l)^2}$ and $e_S^{\mathrm{SO}} = \frac{x(r+l)^2-l\theta}{1-(r+l)^2}$, respectively.

Proposition 1 reveals that under complete information, the brand owner only gives the supplier a positive up-front payment ($P^{\mathrm{SO}} > 0$) and does not require any warranty payment ($W^{\mathrm{SO}} = 0$) from the supplier. Moreover, the up-front payment is equal to the supplier's quality effort cost. This is because the brand owner knows the supplier's inherent quality level accurately and can observe the supplier's quality effort so that it can command the supplier to invest the optimal effort in producing component. Thus, it is unnecessary to punish the supplier for bad component or incentivise the supplier for higher quality investment. The brand owner just needs to compensate the supplier for the cost of its effort to ensure participation.

Interestingly, Proposition 1 also suggests that the first-best quality efforts of both the brand owner and the supplier are decreasing in the rate of defect discovery. That is, if the incoming inspection is inaccurate, the brand owner should provide more efforts to improve the quality of manufacturing so as to remedy the deficiency in the component. Synergistically, the brand owner would let the supplier put in more investment in enhancing the quality in producing the component in order to lower the accuracy requirement of the inspection. Note that e_B^{SO} is increasing in x; that is, the manufacturer also needs to make more effort, even though the suppliers inherent quality level x becomes high. That is because, must both the component and the manufacturing process be in good quality, can the finished product be in good quality. Hence, even though the suppliers inherent quality level x becomes high, i.e., the supplier can provide high-quality components, the manufacturer also needs to make effort in the manufacturing process to enhance the final product quality $(x + e_S)e_B$.

Based on the concrete warranty contract and the exact efforts specified in Proposition 1, we derive the brand owner's and the supplier's first-best profits in the following corollary.

Corollary 1: In Case SO, the supplier's optimal expected profit is given by

$$\pi_S^{\mathrm{SO}} = 0$$

and the brand owner's optimal expected profit is given by

$$\pi_B^{\mathrm{SO}} = E\left[\frac{\left[(r+l)^2x - l\theta\right]^2}{2\left[1-(r+l)^2\right]} + A\right],$$

where $A = \frac{1}{2}(r+l)^2x^2 - l[1-(1-x)\theta] - I$.

As shown in Corollary 1, the brand owner extracts the supplier's all surplus value. Furthermore, the brand owner benefits better with higher level of the supplier's inherent quality level and higher ratio of the inspection process identifying a defective component. The first-best results in this case can also serve as a reference for the other cases to be addressed below.

B. Unobservable quality efforts

In this case, we examine the situation in which the supplier's inherent quality level is in public domain, i.e., it is a piece of public information. However, neither the brand owner nor the supplier can observe each other's quality effort. The brand owner and the supplier choose their respective qualities as a self-interest maximiser, that is, the choice of quality effort maximises their own expected profits after agreeing on the warranty contract. Such behaviours bring about double moral hazard problem for the brand owner, which leads to the following optimisation model.

$$\begin{cases} \max\limits_{\{P,W\}} \pi_B & \text{(OBJ–SU)} \\ \text{subject to:} & \\ \quad \hat{e}_B = \arg\max\limits_{e_B} \pi_B, & \text{(ICB)} \\ \quad \hat{e}_S = \arg\max\limits_{e_S} \pi_s(x,x), & \text{(ICS1)} \\ \quad \pi_S(x,x)\ \big|_{e_S=\hat{e}_S} \geqslant 0. & \text{(IRS)} \end{cases}$$

The following proposition presents closed-form solutions to the optimal warranty contract and the optimal quality investment that the brand owner and the supplier should follow in the presence of double moral hazard.

Proposition 2: In Case SU, the optimal warranty contract is given by $P^{\mathrm{SU}} = (1-x)\left[\frac{x(r+l)^2-l\theta}{1-(r+l)^2}\right] - \frac{1}{2}\left[\frac{x(r+l)^2-l\theta}{1-(r+l)^2}\right]^2$ and $W^{\mathrm{SU}} = \frac{(r+l)^2x-l\theta}{[1-(r+l)^2]\theta}$. The quality efforts of brand owner and the supplier are $e_B^{\mathrm{SU}} = \frac{(x-l\theta)(r+l)}{1-(r+l)^2}$ and $e_S^{\mathrm{SU}} = \frac{x(r+l)^2-l\theta}{1-(r+l)^2}$, respectively.

Proposition 2 reveals two important points. First, it is optimal for the brand owner to put a positive weight on warranty payment under double moral hazard. Hence, the supplier gets incentives for providing quality effort. Also, the warranty based on the information from incoming inspection increases as the product's unit revenue r and the inherent quality level x becomes higher. Specially, the warranty payment increases as the ratio of the inspection process identifying a defective component θ decreases. That is because, based on the definition of component rejection rate $(1-x-e_S)\theta$, a higher chance that the defective components are identified, the supplier would have to enhance his quality effort for reducing the penalty and component rejection rate. Furthermore, based on the incentive compatibility constraint for moral hazard: $e_S^{SU} = \theta W^{SU}$, the higher the warranty payment is, the higher the supplier's quality effort is. The brand owner has no need to provide higher warranty payment for a higher-effort supplier Thus, a higher chance that the defective components are identified, the less warranty payment is charged by the brand owner. Second, the first-best quality efforts result in under this optimal warranty contract in Case SU. That is, even though the brand owner's and the supplier's quality efforts are not observable and contractible to each other, the up-front payment P^{SU} and the warranty payment W^{SU} help to encourage the supplier and the brand owner to choose the first-best quality investment.

Corollary 2: In Case SU, the supplier's optimal expected profit is given by

$$\pi_S^{\mathrm{SU}} = 0$$

and the brand owner's optimal expected profit is given by

$$\pi_B^{\mathrm{SU}} = E\left[\frac{\left[(r+l)^2x-l\theta\right]^2}{2\left[1-(r+l)^2\right]} + A\right].$$

Corollary 2 indicates that the brand owner can achieve the first-best profit by designing the optimal contract given in Proposition 2. Furthermore, unlike the standard positive agency cost which indicates the supplier's net profit in the quality management literature under double moral hazard (e.g., [9] and [14]), our analytical result in Corollary 2 implies that the agency cost is equal to zero (i.e., $\pi_S^{\mathrm{SU}} = 0$).

Note that the above different finding on agency cost not only complements the result obtained in the traditional quality improvement study, but also offers potential usefulness in conducting future empirical research. Further studies on incentive mechanism are required to find the root reason causing the difference of agency cost between this work and certain existing results reported in the literature (e.g., [9] and [14]), of course.

V. Optimal Solutions under Asymmetric Inherent Quality Level

In this section, we consider the case where the inherent quality level is the private information of the supplier. The main objective of this investigation is to establish the optimal warranty contract parameters and to obtain the brand owner's and the supplier's optimal profits when there is asymmetric information regarding the supplier's inherent quality level.

A. Observable quality efforts

We begin by analysing the pure adverse selection case, that is, the brand owner can observe the supplier's quality effort, but does not truthfully know the supplier's inherent level. Thus, the brand owner's incentive compatibility constraint for moral hazard ICB and the supplier's incentive compatibility constraint for moral hazard ICS1 are no longer needed. The brand owner inevitably wishes to maximise its expected profit, which is subject to two constraints on the supplier's profit: the incentive compatibility constraint for adverse selection and the individual rationality constraint. To reflect this observation, the brand owner's optimisation problem can be represented by

$$\begin{cases} \max\limits_{\{P,W,e_S,e_B\}} \pi_B & \text{(OBJ–AO)} \\ \text{subject to:} & \\ \quad \pi_S(x,x) \geqslant \pi_S(x,\tilde{x}), & \text{(ICS2)} \\ \quad \pi_S(x,x) \geqslant 0. & \text{(IRS)} \end{cases}$$

This design problem can be resolved according to the revelation principle by the brand owner [45]. Indeed, the direct revelation principle restricts the supplier to choosing the unique contract that can reveal the inherent quality level truthfully. Therefore, to solve this model, we first present two lemmas that simplify the brand owner's problem.

Lemma 1: In Case AO, the optimal warranty contract satisfies the supplier's incentive compatibility for adverse selection and individual rationality constraints if and only if

1) $\dfrac{\mathrm{d}P(x)}{\mathrm{d}x} - (1-x-e_S)\,\theta\dfrac{\mathrm{d}W(x)}{\mathrm{d}x} = 0, \quad \forall x \in [0,1];$
2) $\dfrac{\mathrm{d}W(x)}{\mathrm{d}x} \geqslant 0, \quad \forall x \in [0,1];$
3) $\pi_S(\underline{x},\underline{x}) = 0.$

Lemma 1 provides conditions under which the ICS1 and IRS constraints are satisfied. As such, this lemma simplifies the expressions for the ICS1 and IRS constraints. Based on it, we can further simplify the expression of the brand owner's expected profit presented in the next lemma.

Lemma 2: In Case AO, the brand owner's expected profit can be written as

$$\pi_B^{\mathrm{AO}} = E\left[r(x+e_S)e_B - lf - S - M - I - \theta H(x)W(x)\right].$$

This lemma provides a convenient way to express the brand owner's expected profit. According to Lemmas 1 and 2, the brand owner's optimisation problem can be transformed into

$$\begin{cases} \max\limits_{\{P(x),W(x),e_S,e_B\}} \pi_B^{\mathrm{AO}} \\ \text{subject to:} \\ \quad \dfrac{\mathrm{d}W(x)}{\mathrm{d}x} \geqslant 0, \quad \forall x \in [0,1]. \end{cases}$$

The next proposition characterises the optimal menu of warranty contracts and optimal quality efforts in the presence of asymmetric information about the supplier's inherent quality level without double moral hazard.

Proposition 3: In Case AO, the optimal warranty contract is given by $P^{\mathrm{AO}} = \frac{1}{2}\left[\frac{x(r+l)^2-l\theta}{1-(r+l)^2}\right]^2$ and $W^{\mathrm{AO}} = 0$. The quality effort of brand owner and that of the supplier are $e_B^{\mathrm{SO}} = \frac{(x-l\theta)(r+l)}{1-(r+l)^2}$ and $e_S^{\mathrm{SO}} = \frac{x(r+l)^2-l\theta}{1-(r+l)^2}$, respectively.

Surprisingly, we find that if the brand owner's and the supplier's efforts are observable and the inherent quality level is private, from the perspective of brand owner, it can just offer the supplier the up-front payment but does not let the supplier undertake the warranty payment. Moreover, the first-best quality efforts can also be realised. That is, the asymmetric information regarding the inherent quality level cannot deter the supplier and the brand owner from optimal quality investment by agreeing on the optimal warranty contract as shown in Proposition 3.

In the case of pure adverse selection without double moral hazard, the brand owner's optimal payoff and the supplier's optimal payoff can be described as follows:

Corollary 3: In Case AO, the supplier's optimal expected profit is given by

$$\pi_S^{\mathrm{AO}} = 0$$

and the brand owner's optimal expected profit is given by

$$\pi_B^{\mathrm{AO}} = E\left[\frac{\left[(r+l)^2x - l\theta\right]^2}{2\left[1-(r+l)^2\right]} + A\right].$$

Corollary 3 implies an interesting feature of the pure adverse selection case that in spite of the incomplete information about the supplier's inherent quality level, the brand owner can still reap the first-best profit from supply chain partner. By designing the optimal contract, it can completely eliminate the need for the brand owner to conduct screening for the inherent quality level and also, to avoid the information expenses required to pay for the supplier in order to gain the private information truthfully from the supplier.

B. Unobservable quality efforts

In this case, we discuss the situation where the inherent quality level is supplier's private information and neither the supplier's quality effort nor brand owner's quality effort is observable and contractible. Hence, in addition to the adverse selection problem, the brand owner faces a double moral hazard problem. We intend to investigate how the brand owner screen the supplier's inherent quality level as well as to induce quality improvement effort by designing the optimal menu of warranty contracts based on the defective rate through incoming inspection.

Taking into account both the brand owner's and the supplier's incentive compatibility constraint, as well as the supplier's participation constraint, the brand owner's optimisation problem can be modeled by

$$\begin{cases} \max\limits_{\{P,W\}} \pi_B & \text{(OBJ–AU)} \\ \text{subject to:} & \\ \quad \hat{e}_B = \arg\max\limits_{e_B} \pi_B(e_B), & \text{(ICB)} \\ \quad \hat{e}_S = \arg\max\limits_{e_S} \pi_S(e_S), & \text{(ICS1)} \\ \quad \pi_S(x,x)\big|_{e_S=\hat{e}_S} \geqslant \pi_S(x,\tilde{x})\big|_{e_S=\hat{e}_S}, & \text{(ICS2)} \\ \quad \pi_S(x,x)\big|_{e_S=\hat{e}_S} \geqslant 0. & \text{(IRS)} \end{cases}$$

To resolve this sophisticated problem, we first simplify the expressions ICB, ICS1, ICS2 and IRS and find the equivalence of the constraints in the following lemma.

Lemma 3: For any given $x \in [0,1]$, the optimal warranty contract satisfies the incentive compatibility constraints and individual rationality constraint if and only if

1) $(\hat{e}_S, \hat{e}_B) = (\theta W(x), (r+l)\theta W(x))$;
2) $\dfrac{\mathrm{d}P(x)}{\mathrm{d}x} - (1-x)\,\theta\dfrac{\mathrm{d}W(x)}{\mathrm{d}x} + \dfrac{1}{2}\theta^2 W(x)\dfrac{\mathrm{d}W(x)}{\mathrm{d}x} = 0, \quad \forall x \in [0,1]$;
3) $\dfrac{\mathrm{d}W(x)}{\mathrm{d}x} \geqslant 0, \quad \forall x \in [0,1]$;
4) $\pi_S(\underline{x},\underline{x}) = 0$.

Based on Lemma 3, we can further simplify the expression of the brand owner's expected profit in the next lemma.

Lemma 4: In Case AU, the brand owner's expected profit can be written as

$$\begin{aligned} \pi_B^{\mathrm{AU}} = \; & E[\tfrac{1}{2}\left[(r+l)^2 - 1\right]\theta^2 W^2(x) \\ & + [(r+l)^2x - l\theta - H(x)]\theta W(x) + A]. \end{aligned}$$

Based on Lemmas 3 and 4, the brand owner's optimisation problem can be transformed into

$$\begin{cases} \max\limits_{W(x)} \pi_B^{\mathrm{AU}} \\ \text{subject to:} \\ \quad \dfrac{\mathrm{d}W(x)}{\mathrm{d}x} \geqslant 0, \quad \forall x \in [0,1]. \end{cases}$$

This brand owner's problem can be analytically solved and the optimal menu of warranty contracts determined as given in the following proposition.

Proposition 4: In Case AU, the optimal warranty contract takes the following form: $P^{\mathrm{AU}}(x) = \frac{(1-x)\left[(r+l)^2x - H(x) - l\theta\right]}{1-(r+l)^2} - \frac{\left[(r+l)^2x - H(x) - l\theta\right]^2}{2[1-(r+l)^2]^2} + \int_{\underline{x}}^{x} \frac{(r+l)^2y - H(y) - l\theta}{1-(r+l)^2}\mathrm{d}y$ and $W^{\mathrm{AU}}(x) = \frac{(r+l)^2x - H(x) - l\theta}{[1-(r+l)^2]\theta}$. The quality effort of brand owner and that of the supplier are $e_B^{\mathrm{AU}} = \frac{(r+l)[x - H(x) - l\theta]}{1-(r+l)^2}$ and $e_S^{\mathrm{AU}} = \frac{(r+l)^2x - H(x) - l\theta}{1-(r+l)^2}$.

Proposition 4 has the following implications. First, if the brand owner faces both adverse selection and double moral hazard problems, the supplier should be asked to provide a positive warranty payment. In addition, the warranty payment increases along with the supplier's inherent quality level. In other words, the brand owner prefers to upgrade the warranty for a higher quality level of supplier, which helps decrease the likelihood that the supplier selects other contracts for mimicking the lower type. Second, we find that the supplier's optimal quality effort in Case AU is smaller than its first-best effort; the brand owner's optimal effort has the same property. This is because given a certain quality of a finished component, the higher the inherent quality, the less effort the supplier needs to invest. Thus, the supplier intends to reduce its effort cost by misreporting the truthful inherent quality level.

Note that by this proposition, we can compute both the supplier's and the brand owner's expected profit, as described in the following corollary.

Corollary 4: In Case AU, the supplier's optimal expected profit is given by

$$\pi_S^{\mathrm{AU}} = \int_{\underline{x}}^{x} \frac{(r+l)^2 y - H(y) - l\theta}{1-(r+l)^2} \mathrm{d}y$$

and the brand owner's optimal expected profit is given by

$$\pi_B^{\mathrm{AU}} = E\left[\frac{\left[(r+l)^2 x - l\theta - H(x)\right]^2}{2\left[1-(r+l)^2\right]} + A\right].$$

In the presence of adverse selection followed by double moral hazard, the supplier has a positive agency cost. The brand owner cannot fully extract the supplier's surplus. In this case, the brand owner has to pay to obtain the supplier information, by inducing the supplier to report its inherent quality information truthfully while exerting the optimal effort to enhance the component quality.

VI. Comparative Studies

So far we have presented analytical results and provided theoretical insights into the properties of the optimal menu of contracts and brand owner's and supplier's profits under four information cases. In this section, we compare the results on the final product's quality, the optimal warranty contract and the supply chain partners' profits that are achievable in the different information scenarios. This is carried out in order to investigate the implications of information asymmetry. We shall perform an extensive experimental investigation quantitatively, presenting our results graphically to ease the exposition apart from qualitative analysis. Particularly, we will address the following questions regarding the value of information: What is the effect of information asymmetry on the optimal contracting strategies? How much does knowing the information about the supplier's inherent quality level, or observing both partners' efforts, help to improve the final product's quality? Under what circumstances is the value of information significant, for the purpose of diminishing the agency cost and improving the brand owner's profit?

A. Effects of information asymmetry on contracting strategies

We begin with characterising the variance of the optimal warranty contract among the four information cases examined. As the up-front payment is determined by the warranty payment through the supplier's participant constraint, the warranty payment plays the essential role in incentive. Thus, for tractability and practicality, we mainly focus on studying the differences of the warranty payment in four information cases. Based on Propositions 1-4, we can compare and show their diversification in the following proposition.

Proposition 5: The optimal warranty payments in the four information cases have the following relationship: $W^{\mathrm{SU}}(x) \geqslant W^{\mathrm{AU}}(x) > W^{\mathrm{AO}}(x) = W^{\mathrm{SO}}(x) = 0$.

In view of this proposition, the optimal warranty payment under pure adverse selection is the same as that under complete information. That is, even though the supplier's inherent quality level is unknown to the brand owner, the brand owner can still design the first-best contract for the supplier. This result holds for the situations with pure hidden information. However, it will make a difference under hidden actions, i.e., the optimal warranty payment will be distorted upwards under double moral hazard no matter whether the inherent quality level is public or private. Hence, when the quality efforts themselves become independent decision variables rather than those decided by the brand owner, the brand owner should ensure the supplier to provide a positive warranty aiming at encouraging it to make appropriate effort for improving its product quality.

Proposition 5 also implies that the optimal warranty payment under double moral hazard is higher than that under combination case with both double moral hazard and adverse selection. This is because the supplier can have motivations to conceal true information and mimic other lower levels of inherent quality under both adverse selection and double moral hazard. Consequently, the brand owner has to shrink the warranty payment to avoid such strategic behavior. We also observed that the optimal warranty payment under combination case has its maximum value, which equals that under pure double moral hazard as the supplier's inherent quality reaches the upper bound (i.e., $x = \bar{x}$).

B. Effects of information asymmetry on both parties' profits

In this sub-section, we aim to investigate the impact of the supplier's private information regarding the inherent quality level and double moral hazard upon the brand owner's profit. This work may contribute to certain managerial insights of diminishing the detrimental influences caused by information asymmetry.

Note that we can intuitively derive that the brand owner can achieve the first-best profit under pure adverse selection case and pure double moral hazard case. To investigate the value of perfect information, we compare the brand owner's optimal expected profit in the complete information case with that in the combination case involving both double moral hazard and adverse selection through the following measurements:

$$\mathrm{VI_B} = \pi_{\mathrm{B}}^{\mathrm{SO}} - \pi_{\mathrm{B}}^{\mathrm{AU}},$$

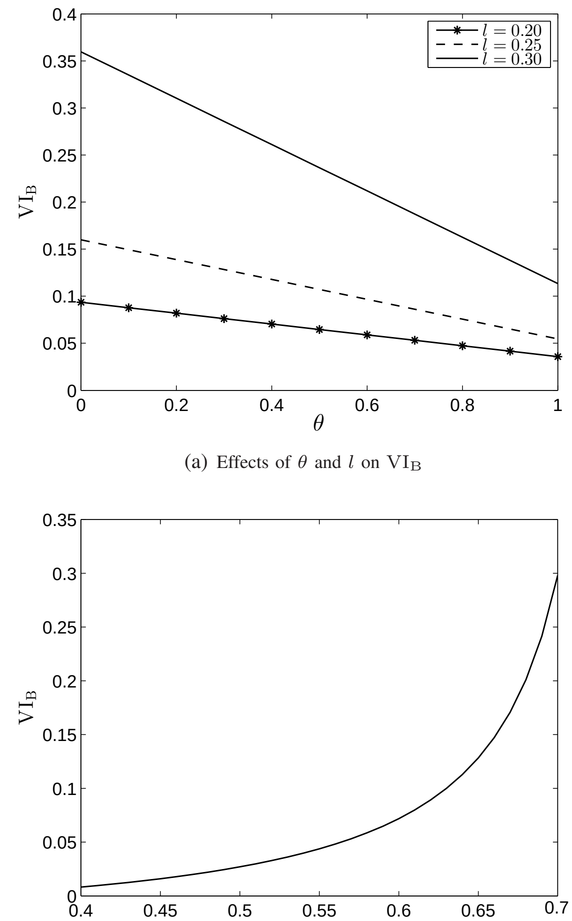
$$\mathrm{VI_S} = \pi_{\mathrm{S}}^{\mathrm{AU}} - \pi_{\mathrm{S}}^{\mathrm{SO}}.$$

In the above, $\mathrm{VI_B}$ denotes the value of information asymmetry from the brand owner's viewpoint, standing for the increase in the brand owner's expected profit if it can acquire the supplier's hidden information and hidden action. In contrast, $\mathrm{VI_S}$ is the value of information asymmetry for the supplier, which indicates the profit increase in the supplier's agency cost. $\pi_{\mathrm{B}}^{\mathrm{SO}}$ and $\pi_{\mathrm{S}}^{\mathrm{SO}}$ are the brand owner's and supplier's expected profit under the complete information case given in Corollary 1, and $\pi_{\mathrm{B}}^{\mathrm{AU}}$ and $\pi_{\mathrm{S}}^{\mathrm{AU}}$ are those under both double moral hazard and adverse selection as per Corollary 4.

Proposition 6: The value of information asymmetry for both the brand owner and the supplier mainly depends on three key factors: the unit price r, the replacement/refund cost l, and the defective rate θ detected by incoming inspection. In particular, $\mathrm{VI_B}$ and $\mathrm{VI_S}$ are both decreasing in θ and increasing in r and l.

Proposition 6 exhibits the differences of the brand owner's and the supplier's profits between the complete information case and the combination case with both double moral hazard and adverse selection. We show that the value of information asymmetry for both the brand owner and the supplier are decreasing in relation to the accuracy of the inspection process that identifies a defective component, whilst being increasing in relation to the unit price and the failure cost. In addition, the value of information is unaffected by the inspection cost because the inspection cost is fixed and holds no relationship with the component defective rate or the accuracy of the inspection process.

Having already demonstrated the value of the information on both parties' profits analytically, we shall perform numerical studies in which the values of parameters come from the real data in a Chinese automotive enterprise to strengthen the illustration of the results explicitly. In the following numerical analysis, to investigate potential challenging situations, we obtain that the supplier's inherent quality level x is defined on a wide support of $[0.5, 0.9]$ by the estimation of a relevant manager of a Chinese automotive enterprise, while obeying linear uncertainty distribution. Meanwhile, the other parameters' values, such as θ, r and l are also obtained by interviewing this manager. We present the result of Proposition 6 in Figure 1, in terms of the three key factors as identified in the proposition.



(a) Effects of θ and l on $\mathrm{VI_B}$

(b) Effects of r on $\mathrm{VI_B}$

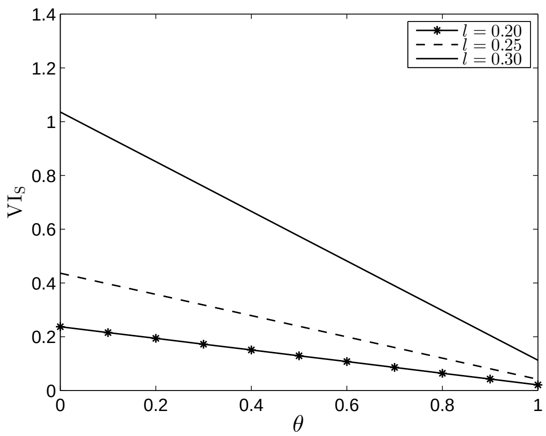
Fig. 1. Effects on value of information asymmetry for brand owner
NB. Parameters used are: $r = 0.65$ in Fig. 2(a); $\theta = 0.3$ and $l = 0.25$ in Fig. 2(b).

As shown in Figure 1, the asymmetric information combining with hidden actions and hidden quality level information is particularly valuable to the brand owner when the unit loss caused by the product failure is higher or the unit product has a very expensive price. This is because knowing the supplier's truthful inherent quality level and contracting on both supply chain partners' quality efforts can significantly reduce the expenses for information retained by the supplier while improving the product quality. As such, the potential loss due to bad products decreases and the revenue obtained from quality products sold in the market increases. Therefore, for a product with higher replacement/refund cost and higher unit price, it is critical for the brand owner to acquire information on supplier's truthful inherent quality level and to observe its quality effort.

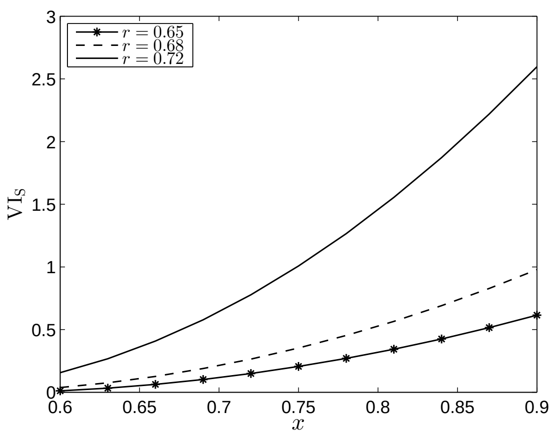
Figure 1 also illustrates that the more inaccurate the brand owner's inspection process is, the less valuable the incomplete information is to the brand owner. That is to say, it is more profitable for the brand owner to screen the supplier's private information about inherent quality level and to ensure the supplier's effort to be observable and contractible as the inspection process cannot effectively identify defective components.

Figure 2 reveals the potential influence of the three key parameters on the value of asymmetric information for the supplier. From the plots within this figure, we can also find that the value of asymmetric information for the supplier is equal to its own sole agency cost under the combination case with both double moral hazard and adverse selection. Thus, the supplier can receive more agency cost when the product's price is higher, the replacement/refund cost is larger, or the inspection process has a lower precision. This is of course expected, demonstrating the correctness of the proposed work.

By comparing the simulation results in Figure 1 and Figure 2, it is shown that the monotonicity of the value of information asymmetry with respect to the parameters θ, l and r for the supplier is the same to that for the brand owner. This is because the agency cost is also considered as an expense for gaining information. Consequently, the simulation results in Figure 1 and Figure 2 can also validate our analytical results in Proposition 6, such that the value of information for the brand owner and that for the supplier are both decreasing in relation to θ and increasing in response to r and l.



(a) Effects of θ and l on $\mathrm{VI_S}$



(b) Effects of r on $\mathrm{VI_S}$

Fig. 2. Effects on value of information asymmetry for the supplier
NB. Parameters used are: $x = 0.8$ and $r = 0.6$ in Fig. 2(a); $\theta = 0.3$ and $l = 0.25$ in Fig. 2(b).

VII. Conclusions

This paper has presented an approach that is intended to model the contracting relationship between a brand owner and a supplier. The brand owner who manufactures a product imports components from a supplier, and there is incomplete information regarding the supplier's inherent quality level whilst the quality efforts of the brand owner and supplier are generally and mutually unobservable. Using insights from uncertainty theory and principal-agent theory, we characterise the optimal warranty mechanism and the levels of effort the brand owner and the supplier would exert under four information scenarios. For each case, the work captures the brand owner's and the supplier's profits. This work has also investigated the potential impact of information asymmetry regarding double moral hazard and adverse selection on the optimal warranty contract, quality investment and the supply chain partners' profits.

The paper has shown that the brand owner may only need to pay the supplier a fixed up-front payment without any warranty in the complete information or pure adverse selection case. Warranty payment should be designed to induce the supplier's quality improvement effort if the supplier's effort is unobservable. Particularly, warranty payment should increase as the product's unit price or the inherent quality level becomes higher, or as the ratio of the inspection process that identifies a defective component decreases. When the brand owner encounters both double moral hazard and adverse selection, the optimal warranty payment should be lower than that when the brand owner encounters pure double moral hazard problem, thereby preventing the supplier mimicking other lower levels of inherent quality. If the brand owner adopts the optimal warranty contract as proposed, the first-best quality investment can be achieved if there exists one-dimensional asymmetric information between the brand owner and the supplier. However, double moral hazard together with adverse selection may lead to under-investment in quality efforts.

Note that the brand owner can achieve the first-best profit when either the supplier's inherent quality level becomes public information or both supply chain partners' efforts are contractible. Thus, the existence of pure adverse selection problem or pure double moral hazard problem does not add any additional information cost for the brand owner. This result implies that as the brand owner's problem generally involves both adverse selection and double moral hazard it may suffer from an unnecessary loss. The work has further demonstrated that such a loss increases in response to the unit price and the failure cost while decreasing in relation to the accuracy of the inspection process utilised to identify defective components. This suggests that from the brand owner's profit maximisation perspective, it will be beneficial to have more inferior inspection and better information about the supplier's private information with higher product's unit price, and hence less overall failure cost.

Future work will include the examination of the contracting relationship between the brand owner and the consumers and its impact upon the warranty contract for the supplier. Our work can also be extended to investigating the optimal menu of warranty contract under dual information asymmetry within alternative quality management mechanisms, e.g., the supplier certification approach [2] and the failure-based approach [46].

Acknowledgements

The authors would like to thank Department Editor Prof. S. Talluri and the anonymous reviewers.

Appendix

Proof of Proposition 1. In the framework of principal-agent theory, the supplier's individual rationality constraint (IRS) binds at optimality. Consequently, we can substitute the up-front payment into the brand owner's objective function and obtain:

$$\begin{aligned}\pi_B = \quad & r(x+e_S)e_B - l[1-(x+e_S)e_B - (1-x-e_S)\theta] \\ & -\tfrac{1}{2}e_S^2 - \tfrac{1}{2}e_B^2 - I.\end{aligned}$$

Here, to guarantee that the brand owner's or the supplier's marginal quality effort profit is higher than their respective marginal effort cost, we assume that $(r+l)<1$. The first-order conditions with respect to e_S and e_B are given by $e_S=(r+l)e_B-l\theta$ and $e_B=(r+l)(x+e_S)$, respectively. By using the method of simultaneous solution, we have $e_B^{\mathrm{SO}}=\frac{(x-l\theta)(r+l)}{1-(r+l)^2}$ and $e_S^{\mathrm{SO}}=\frac{x(r+l)^2-l\theta}{1-(r+l)^2}$. In the condition of complete information, the brand owner knows the supplier's inherent quality level while the quality efforts are observable. Thus, the brand owner does not need the warranty for providing incentive, i.e., $W^{\mathrm{SO}}=0$. Substituting the optimal quality efforts above into the binding individual rationality constraint, the corresponding optimal up-front payment can be derived immediately: $P^{\mathrm{SO}}=\frac{1}{2}\left[\frac{x(r+l)^2-l\theta}{1-(r+l)^2}\right]^2$. The proof of the proposition is complete.

Proof of Proposition 2. In Case SU, the brand owner and the supplier will choose the quality efforts by themselves to maximise their own utility. By the first-order condition of the supplier's profit with respect to e_S, the supplier's optimal effort level can be derived such that it satisfies the incentive compatibility constraint for moral hazard: $\hat{e}_S=\theta W$. Substituting the supplier's optimal effort into the brand owner's profit function and then take the derivative of the brand owner's profit function with respect to e_B, we obtain $\hat{e}_B=(r+l)(x+\theta W)$. Therefore, the brand owner's profit becomes

$$\begin{aligned}\pi_B= & -\tfrac{1}{2}[1-(r+l)^2]\theta^2W^2+[(r+l)^2x\theta-l\theta^2]W\\ & +\tfrac{1}{2}(r+l)^2x^2-I-l[1-(1-x)\theta].\end{aligned}$$

By the first-order condition regarding to the warranty payment, we obtain $W^{\mathrm{SU}}=\frac{(r+l)^2x-l\theta}{[1-(r+l)^2]\theta}$. Since $e_S=\theta W$ and $e_B=(r+l)(x+\theta W)$, the brand owner's and the supplier's optimal quality investment are therefore, given by $e_B^{\mathrm{SU}}=\frac{(x-l\theta)(r+l)}{1-(r+l)^2}$ and $e_S^{\mathrm{SU}}=\frac{x(r+l)^2-l\theta}{1-(r+l)^2}$, respectively. Based on the supplier's binding individual rationality constraint, the optimal up-front payment P can be obtained immediately. The proof of the proposition is complete.

Proof of Lemma 1. Since

$$\pi_S(x,x)\geqslant\pi_S(x,\tilde{x}),\quad\forall x,\tilde{x}\in[\underline{x},\overline{x}],$$

if a quality level x supplier reports as another quality level $\tilde{x}$, its expected payoff should be less than that achievable while telling the truth. This is governed by the revelation principle which implies that the supplier can receive its maximal profit $\pi_S(x,x)$ if and only if $\tilde{x}=x$. Thus, $\pi_S(x,\tilde{x})$ satisfies the first-order condition, i.e., the local incentive compatibility constraint:

$$\frac{\partial\pi_S(x,\tilde{x})}{\partial\tilde{x}}\Big|_{\tilde{x}=x}=\frac{\mathrm{d}P(x)}{\mathrm{d}x}-(1-x-e_S)\theta\frac{\mathrm{d}W(x)}{\mathrm{d}x}=0\quad(1)$$

and also the second-order condition:

$$\frac{\partial^2\pi_S(x,\tilde{x})}{\partial\tilde{x}^2}\Big|_{\tilde{x}=x}=\frac{\mathrm{d}^2P(x)}{\mathrm{d}x^2}-(1-x-e_S)\theta\frac{\mathrm{d}^2W(x)}{\mathrm{d}x^2}\leqslant0.\quad(2)$$

Differentiating the local incentive compatibility constraint (1) with respect to x yields

$$\begin{aligned}\frac{\partial^2\pi_S(x,\tilde{x})}{\partial\tilde{x}^2}\Big|_{\tilde{x}=x}= & \frac{\mathrm{d}^2P(x)}{\mathrm{d}x^2}-(1-x-e_S)\theta\frac{\mathrm{d}^2W(x)}{\mathrm{d}x^2}\\ & +\theta\frac{\mathrm{d}W(x)}{\mathrm{d}x}=0.\end{aligned}\quad(3)$$

On the basis of expressions (2) and (3), we obtain the monotonicity condition

$$\frac{\mathrm{d}W(x)}{\mathrm{d}x}\geqslant0,\quad\forall x\in[0,1].\quad(4)$$

Next, suppose that both the local incentive compatibility condition (1) and the monotonicity condition (4) hold. We want to prove that the supplier's incentive compatibility condition for adverse selection holds. Without loss of generality, suppose that $x>\tilde{x}$. By integrating the local incentive compatibility condition (1) and using the monotonicity condition (4), we can obtain

$$\begin{aligned}P(x)-P(\tilde{x}) & =\int_{\tilde{x}}^{x}(1-y-e_S)\theta\frac{\mathrm{d}W(y)}{\mathrm{d}y}\mathrm{d}y\\ & \geqslant(W(x)-W(\tilde{x}))(1-x-e_S)\theta.\end{aligned}$$

Therefore,

$$\pi_S(x,x)\geqslant\pi_S(x,\tilde{x}),\quad\forall x,\tilde{x}\in[\underline{x},\overline{x}].$$

On the other hand, if $x<\tilde{x}$, we can also obtain

$$\begin{aligned}P(\tilde{x})-P(x) & =\int_{x}^{\tilde{x}}(1-y-e_S)\theta\frac{\mathrm{d}W(y)}{\mathrm{d}y}\mathrm{d}y\\ & \leqslant(W(\tilde{x})-W(x))(1-x-e_S)\theta.\end{aligned}$$

That is to say

$$\pi_S(x,x)\geqslant\pi_S(x,\tilde{x}),\quad\forall x,\tilde{x}\in[\underline{x},\overline{x}].$$

Finally, we need to prove the monotonicity condition and the local incentive compatibility condition. Using the first-order condition of $\pi_S(x,x)$ with respect to x yields

$$\frac{\mathrm{d}\pi_S(x,x)}{\mathrm{d}x}=\theta W(x)\geqslant0.$$

Hence, the supplier's individual rationality constraint is equivalent to

$$\pi_S(\underline{x},\underline{x})=0.$$

The proof of the lemma is complete.

Proof of Lemma 2. According to

$$\pi_S(x,x)=\int_{\underline{x}}^{x}\theta W(x)\mathrm{d}t-\pi_S(\underline{x},\underline{x}),$$

we derive the definitional equation of the up-front payment

$$P(x)=(1-x-e_S)\theta W(x)-\frac{1}{2}e_S^2+\int_{\underline{x}}^{x}\theta W(y)\mathrm{d}y.$$

Substituting the up-front payment into the brand owner's expected profit yields

$$\begin{aligned}\pi_B^{\mathrm{AO}}= & E[r(X+e_S)e_B-l[1-(X+e_S)e_B\\ & -(1-X-e_S)\theta]-\tfrac{1}{2}e_S^2-\tfrac{1}{2}e_B^2-I-\theta H(X)W(X)].\end{aligned}$$

The proof of the lemma is complete.

Proof of Proposition 3. The brand owner's expected profit decreases in relation to $W(x)$. Consequently, $W(x)=0$. Furthermore, using the first-order condition $\frac{\partial\pi_B}{\partial e_B}=0$ and $\frac{\partial\pi_B}{\partial e_S}=0$ leads to the optimal effort levels: $e_B^{\mathrm{AO}}=\frac{(x-l\theta)(r+l)}{1-(r+l)^2}$ and $e_S^{\mathrm{AO}}=\frac{x(r+l)^2-l\theta}{1-(r+l)^2}$. The corresponding optimal up-front payment $P(x)$ can be obtained by its definition subsequently. The proof of the proposition is complete.

Proof of Lemma 3. By using the first-order condition $\frac{\partial\pi_S}{\partial e_S}=$

0, the supplier selects its own optimal effort $\hat{e}_S = \theta W$. Thus, when the supplier reports the inherent quality level with x truthfully, its expected utility

$$\pi_S(x,x)\mid_{e_S=\hat{e}_S} = P(x) - (1-x)\theta W(x) + \frac{1}{2}\theta^2 W^2(x).$$

However, if the supplier misreports the inherent quality level with $\tilde{x}$, the expected utility becomes

$$\pi_S(x,\tilde{x})\mid_{e_S=\hat{e}_S} = P(\tilde{x}) - (1-x)\theta W(\tilde{x}) + \frac{1}{2}\theta^2 W^2(\tilde{x}).$$

The rest of the proof is similar to the Proof of Lemma 1. The proof of the lemma is complete.

Proof of Lemma 4. Similar to the Proof of Lemma 2.

Proof of Proposition 4. By using the similar method as used in the Proof of Proposition 3 and ignoring the monotonicity condition on $W(x)$, the brand owner's maximisation problem can be rewritten as

$$\begin{aligned}\max_{W(x)} E \quad &\left[\tfrac{1}{2}\left[(r+l)^2-1\right]\theta^2 W^2(X)\right. \\ &\left.+[(r+l)^2 X - l\theta - H(X)]\theta W(X) + A\right].\end{aligned}$$

The first-order variation of the brand owner's expected profit with regard to $W(x)$ is

$$\begin{aligned}\delta\pi_B = \int_{\underline{x}}^{\overline{x}} \quad &\left[(r+l)^2-1\right]\theta^2 W(x) + \theta[(r+l)^2 x - l\theta - H(x)] \\ &[\delta W(x)] f(x)\mathrm{d}x\end{aligned}$$

and the second-order variation of the brand owner's expected profit is

$$\delta^2\pi_B = \int_{\underline{x}}^{\overline{x}} \theta^2\left[(r+l)^2-1\right] f(x)[\delta W(x)]^2 \mathrm{d}x.$$

By assuming $r+l<1$, we can obtain the optimal warranty payment $W^{\mathrm{AU}}(x) = \frac{(r+l)^2 x - H(x) - l\theta}{[1-(r+l)^2]\theta}$. Based on the relationship between $W(x)$ and $P(x)$, and that between e_B and e_S, we can obtain the corresponding optimal up-front payment, and the brand owner's and the supplier's optimal quality efforts immediately. The proof of the proposition is complete.

Proof of Proposition 5. Observing Propositions 1-4, we can obviously find that $W^{\mathrm{SO}}(x)=0$, $W^{\mathrm{SU}}(x)>0$, $W^{\mathrm{AO}}(x)=0$, $W^{\mathrm{AU}}(x)>0$. In addition,

$$W^{\mathrm{SU}}(x) - W^{\mathrm{AU}}(x) = \frac{H(x)}{\left[1-(r+l)^2\right]\theta} \geqslant 0.$$

Thus, the optimal warranty payments in the four information cases have the following relationship: $W^{\mathrm{SU}}(x) \geqslant W^{\mathrm{AU}}(x) > W^{\mathrm{AO}}(x) = W^{\mathrm{SO}}(x) = 0$. The proof of the proposition is complete.

Proof of Proposition 6. Because

$$\begin{aligned}\mathrm{VI_B} &= \pi_{\mathrm{B}}^{\mathrm{SO}} - \pi_{\mathrm{B}}^{\mathrm{AU}} \\ &= E\left[\tfrac{H(x)[2(r+l)^2 x - 2l\theta - H(x)]}{2[1-(r+l)^2]}\right]\end{aligned}$$

and

$$\begin{aligned}\mathrm{VI_S} &= \pi_{\mathrm{S}}^{\mathrm{AU}} - \pi_{\mathrm{S}}^{\mathrm{SO}} \\ &= \int_{\underline{x}}^{x} \tfrac{(r+l)^2 y - H(y) - l\theta}{1-(r+l)^2}\mathrm{d}y,\end{aligned}$$

both $\mathrm{VI_B}$ and $\mathrm{VI_S}$ are combined with r, l, and θ. Thus, the value of information asymmetry for both the brand owner and the supplier mainly depends on three key factors: the unit price r, the replacement/refund cost l, and the defective rate θ detected by incoming inspection.

Differentiating $\mathrm{VI_B}$ and $\mathrm{VI_S}$ with respect to θ yields

$$\frac{\mathrm{dVI_B}}{\mathrm{d}\theta} = E\left[\frac{-2\theta H(x)}{2\left[1-(r+l)^2\right]}\right] \leqslant 0.$$

and

$$\frac{\mathrm{dVI_S}}{\mathrm{d}\theta} = \frac{-l(x-\underline{x})}{1-(r+l)^2} \leqslant 0,$$

respectively.

Differentiating $\mathrm{VI_B}$ with respect to r yields

$$\frac{\mathrm{dVI_B}}{\mathrm{d}r} = E\left[\frac{H(x)(r+l)[2x-2l\theta-H(x)]}{2\left[1-(r+l)^2\right]^2}\right].$$

Note that we can intuitively derive that the brand owner can achieve the first-best profit under Case SO, hence, $\mathrm{VI_B} \geqslant 0$, i.e., $2(r+l)^2 x - 2l\theta - H(x) \geqslant 0$. Moreover, because $(r+l)<1$, $2x-2l\theta-H(x)>0$. Thus,

$$\frac{\mathrm{dVI_B}}{\mathrm{d}r} = E\left[\frac{H(x)(r+l)[2x-2l\theta-H(x)]}{2\left[1-(r+l)^2\right]^2}\right] > 0.$$

Differentiating $\mathrm{VI_S}$ with respect to r yields

$$\frac{\mathrm{dVI_S}}{\mathrm{d}r} = \int_{\underline{x}}^{x} \frac{2(r+l)(y-H(y)-l\theta)}{[1-(r+l)^2]^2}\mathrm{d}y.$$

Note that $\mathrm{VI_S} = \int_{\underline{x}}^{x} \frac{(r+l)^2 y - H(y) - l\theta}{1-(r+l)^2}\mathrm{d}y \geqslant 0$ and $(r+l)<1$, i.e., $\int_{\underline{x}}^{x} \frac{y-H(y)-l\theta}{1-(r+l)^2}\mathrm{d}y > 0$. Thus,

$$\frac{\mathrm{dVI_S}}{\mathrm{d}r} = \int_{\underline{x}}^{x} \frac{2(r+l)(y-H(y)-l\theta)}{[1-(r+l)^2]^2}\mathrm{d}y > 0.$$

By using the similar method as used in demonstrating $\frac{\mathrm{dVI_B}}{\mathrm{d}r} > 0$ and $\frac{\mathrm{dVI_S}}{\mathrm{d}r} > 0$, $\frac{\mathrm{dVI_B}}{\mathrm{d}l} > 0$ and $\frac{\mathrm{dVI_S}}{\mathrm{d}l} > 0$ can be derived immediately. Therefore, $\mathrm{VI_B}$ and $\mathrm{VI_S}$ are both decreasing in θ and increasing in r and l. The proof of the proposition is complete.

References

[1] Chao, G. H., Iravani, S. M., & Savaskan, R. C. (2009). Quality improvement incentives and product recall cost sharing contracts. *Management Science*, 55(7), 1122–1138.

[2] Chen, Y. J., & Deng, M. (2013). Supplier certification and quality investment in supply chains. *Naval Research Logistics*, 60(3), 175–189.

[3] Liu, B. (2007). Uncertainty Theory (2nd ed.). Berlin: Springer.

[4] Wang, G., Tang, W., & Zhao, R. (2013). An uncertain price discrimination model in labor market. *Soft Computing*, 17(4), 579–585.

[5] Chen, Z., Lan, Y., & Zhao, R. (2018). Impacts of risk attitude and outside option on compensation contracts under different information structures. *Fuzzy Optimization and Decision Making*, 17(1), 13–47.

[6] Zhou, C., Peng, J., Liu, Z., & Dong, B. (2019). Optimal incentive contracts under loss aversion and inequity aver-

sion. *Fuzzy Optimization and Decision Making*, 18(1), 85–102.

[7] Bolton, P., & Dewatripont, M. (2005). Contract Theory. Cambridge, MA: MIT Press.

[8] Babich, V., & Tang, C. S. (2012). Managing opportunistic supplier product adulteration: Deferred payments, inspection, and combined mechanisms. *Manufacturing & Service Operations Management*, 14(2), 301–314.

[9] Dong, Y., Xu, K., Xu, Y., & Wan, X. (2016). Quality management in multi–Level supply chains with outsourced manufacturing. *Production and Operations Management*, 25(2), 290–305.

[10] Farooq, M. A., Kirchain, R., Novoa, H., & Araujo, A. (2017). Cost of quality: Evaluating cost-quality tradeoffs for inspection strategies of manufacturing processes. *International Journal of Production Economics*, 188, 156–166.

[11] Lim, W. S. (2001). Producer-supplier contracts with incomplete information. *Management Science*, 47(5), 709–715.

[12] Baiman, S., Fischer, P. E., & Rajan, M. V., (2001). Performance measurement and design in supply chains. *Management Science*, 47(1), 173–188.

[13] Balachandran, K. R., & Radhakrishnan, S. (2005). Quality implications of warranties in a supply chain. *Management Science*, 51(8), 1266–1277.

[14] Hwang, I., Radhakrishnan, S., & Su, L. (2006). Vendor certification and appraisal: Implications for supplier quality. *Management science*, 52(10), 1472–1482.

[15] Lan, Y., Zhao, R., & Tang, W. (2014). A fuzzy supply chain contract problem with pricing and warranty. *Journal of Intelligent & Fuzzy Systems*, 26(3), 1527–1538.

[16] El Ouardighi, F. (2014). Supply quality management with optimal wholesale price and revenue sharing contracts: A two-stage game approach. *International Journal of Production Economics*, 156, 260–268.

[17] Zeng, J., Zhang, W., Matsui, Y., & Zhao, X. (2017). The impact of organizational context on hard and soft quality management and innovation performance. *International Journal of Production Economics*, 185, 240–251.

[18] Davis, A. M., & Hyndman, K. (2017). An experimental investigation of managing quality through monetary and relational incentives. *Management Science*. https://doi.org/10.1287/mnsc.2016.2716.

[19] Lee, H. H., & Li, C. (2016). Supplier quality management: Investment, inspection, and incentives. *Production and Operations Management*, 27(2), 304–322.

[20] Zhang, M., Guo, H., Huo, B., Zhao, X., & Huang, J. (2019). Linking supply chain quality integration with mass customization and product modularity. *International Journal of Production Economics*, 207, 227–235.

[21] Bray, R. L., Serpa, J. C., & Colak, A. (2019). Supply chain proximity and product quality. *Management Science*. https://doi.org/10.1287/mnsc.2018.3161.

[22] Wu, C. K., Tsang, K. F., Liu, Y., Zhu, H., Wei, Y., Wang, H., & Yu, T. T. (2019). Supply chain of things: A connected solution to enhance supply chain productivity. *IEEE Communications Magazine*, 57(8), 78–83.

[23] Tirkel, I. (2016). The efficiency of inspection based on out of control detection in wafer fabrication. *Computers & Industrial Engineering*, 99, 458–464.

[24] Zhang, J., Huang, X., Fang, Y., Zhou, J., Zhang, H., & Li, J. (2016). Optimal inspection-based preventive maintenance policy for three-state mechanical components under competing failure modes. *Reliability engineering & system safety*, 152, 95–103.

[25] Cheikhrouhou, N., Sarkar, B., Ganguly, B., Malik, A. I., Batista, R., & Lee, Y. H. (2018). Optimization of sample size and order size in an inventory model with quality inspection and return of defective items. *Annals of Operations Research*, 271(2), 445–467.

[26] Gao, Y., & Qin, Z. (2016). On computing the edge-connectivity of an uncertain graph. *IEEE Transactions on Fuzzy Systems*, 24(4), 981–991.

[27] Yang, X., Gao, J., & Ni, Y. (2018). Resolution principle in uncertain random environment. *IEEE Transactions on Fuzzy Systems*, 26(3), 1578–1588.

[28] Yao, K. (2018). Uncertain statistical inference models with imprecise observations. *IEEE Transactions on Fuzzy Systems*, 26(2), 409–415.

[29] Yao, K., & Li, X. (2012). Uncertain alternating renewal process and its application. *IEEE Transactions on Fuzzy Systems*, 20(6), 1154–1160.

[30] Mu, R., Lan, Y., & Tang, W. (2013). An uncertain contract model for rural migrant worker's employment problems. *Fuzzy Optimization and Decision Making*, 12(1), 29–39.

[31] Wu, X., Zhao, R., & Tang, W. (2014). Uncertain agency models with multi-dimensional incomplete information based on confidence level.

[32] Yang, K., Zhao, R., & Lan, Y. (2014). The impact of risk attitude in new product development under dual information asymmetry. *Computers & Industrial Engineering*, 76, 122–137.

[33] Yang, K., Lan, Y., & Zhao, R. (2017). Monitoring mechanisms in new product development with risk-averse project manager. *Journal of Intelligent Manufacturing*, 28(3), 667–681.

[34] Fu, Y., Chen, Z., & Lan, Y. (2018). The impacts of private risk aversion magnitude and moral hazard in R&D project under uncertain environment. *Soft Computing*, 22(16), 5231–5246.

[35] Chen, H., Yan, Y., Ma, N., & Yang, L. (2018). Coopetition strategy and pricing timing in an outsourcing supply chain with uncertain operation risks. *IEEE Transactions on Fuzzy Systems*. DOI: 10.1109/TFUZZ.2018.2821106.

[36] Zhang, W., Wang, X., & Yang, K. (2019). Incentive contract design for the water-rail-road intermodal transportation with travel time uncertainty: A Stackelberg game approach. *Entropy*, 21(2), 161–181.

[37] Zhu, K., Shen, J., & Yao, X. (2019). A three-echelon supply chain with asymmetric information under uncertainty. *Journal of Ambient Intelligence and Humanized Computing*, 10(2), 579–591.

[38] Chen, Z., Lan, Y., Zhao, R., & Shang, C. (2019). Deadline-based incentive contracts in project manage-

ment with cost salience. *Fuzzy Optimization and Decision Making*, 18(4), 451–473.

[39] Dutta, S. (2008). Managerial expertise, private information, and pay-performance sensitivity. *Management Science*, 54(3), 429–442.

[40] Chao, R. O., Lichtendahl, K. C., & Grushka-Cockayne, Y. (2014). Incentives in a stage-gate process. *Production and Operations Management*, 23(8), 1286–1298.

[41] Wan, H., & Xu, X. (2008). Reexamination of all-or-none inspection policies in a supply chain with endogenous product quality. *Naval Research Logistics*, 55(3), 277–282.

[42] Yim, A. (2014). Failure risk and quality cost management in single versus multiple sourcing decision. *Decision Sciences*, 45(2), 341–354.

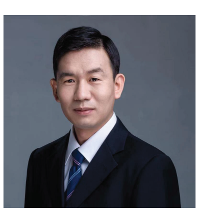
[43] Deng, X., Xie, J., & Xiong, H. (2013). Manufacturer-retailer contracting with asymmetric information on retailer's degree of loss aversion. *International Journal of Production Economics*, 142(2), 372–380.

[44] Yu, X., Lan, Y., & Zhao, R. (2018). Cooperation royalty contract design in research and development alliances: Help vs. knowledge-sharing. *European Journal of Operational Research*, 268(2), 740–754.

[45] Gibbard, A. (1973). Manipulation of voting schemes: A general result. *Econometrica*, 41(4), 587–601.

[46] Bruccoleri, M., Perrone, G., Mazzola, E., & Handfield, R. (2018). The magnitude of a product recall: offshore outsourcing vs. captive offshoring effects. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2018.1533652.

Zhihua Chen received the Ph.D. degree in Management Science and Engineering at the College of Management and Economic, Tianjin University, Tianjin, China, in 2019, and is currently working as Executive Secretary and Supply Chain Manager at the Hangzhou Wahaha Group Co., Ltd., Hangzhou, China. He has co-authored several papers on Fuzzy Optimization and Decision Making, Computers and Industrial Engineering, and Soft Computing. His current research interests include supply chain management and marketing management.



Yanfei Lan received the Ph.D. degree from Tianjin University, Tianjin, China, in 2012. He is currently a professor with College of Management and Economics, Tianjin University. His research interests include optimization under uncertainty, supply chain management, healthcare operations management and so on. He has authored more than 40 articles on international journals including European Journal of Operational Research, Omega, Transportation Research Part A, International Journal of Production Economics, International Journal of Production Research, IEEE Transactions on Engineering Management, Computers and Industrial Engineering and so on. He served as the associate editor of International Journal of Machine Learning and Cybernetics.

Xiang Li received the Ph.D. degree from Tsinghua University, Beijing, China, in 2008. He is currently a professor with School of Economics and Management Science, Beijing University of Chemical Technology. His research interests include intelligent transportation system, optimization under uncertainty, big data analysis and so on. He has authored one book and more than 80 articles on international journals including Applied Mathematical Modelling, Omega, Transportation Research Part B, Transportation Research Part C, Information Sciences, IEEE Transactions on Fuzzy Systems, IEEE Transactions on Systems, Man, and Cybernetics: Systems, IEEE Transactions on Intelligent Transportation Systems, European Journal of Operational Research, Computers and Industrial Engineering and so on, which has been cited more than 2000 times on Web of Science and 3000 times on Google Scholar. He served as the editor-in-chief of Journal of Data, Information and Management, associate editor or editorial board member of Information Sciences, Transportmetrica B, International Journal of General Systems, Journal of Ambient Intelligence and Humanized Computing, Sustainability and so on.

Changjing Shang received the PhD degree in computing and electrical engineering from Heriot-Watt University, Edinburgh, U.K., in 1995. She is currently a University Research Fellow with the Department of Computer Science, Aberystwyth University, Aberystwyth, U.K. Prior to joining Aberystwyth, she was with Heriot-Watt, Loughborough and Glasgow Universities. She has published extensively, and supervised 15 PhDs/PDRAs in the areas of pattern recognition, data mining and analysis, space robotics, and image classification.

Qiang Shen received the PhD degree in computing and electrical engineering from Heriot-Watt University, Edinburgh, U.K., in 1990 and the DSc degree in computational intelligence from Aberystwyth University, Aberystwyth, U.K., in 2013. He is appointed as the Chair of Computer Science and the Pro Vice-Chancellor: Faculty of Business and Physical Sciences, Aberystwyth University, Aberystwyth, U.K. He has authored two research monographs and around 400 peer-reviewed papers. Dr. Shen was a recipient of the Outstanding Transactions Paper Award from the IEEE.